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MEASUREMENTS AND CALCULATIONS OF THE COULOMB CROSS SECTION FOR THE PRODUCTION OF DIRECT ELECTRON PAIRS BY ENERGETIC HEAVY NUCLEI IN NUCLEAR TRACK EMULSION

CENTER DIRECTOR'S DISCRETIONARY FUND FINAL REPORT

By J. H. Derrickson, P. B. Eby, W. F. Fountain,
T. A. Parnell, B. L. Dong, J. C. Gregory,
Y. Takahashi, and D. T. King

Space Science Laboratory
Science and Engineering Directorate

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Prepared by Space Science Laboratory, Science and Engineering Directorate.
[1]School of Science, The University of Alabama in Huntsville, Huntsville, Alabama 35899
[2]Department of Physics, The University of Tennessee at Knoxville, Knoxville, TN

16. ABSTRACT

Measurements and theoretical predictions of the Coulomb cross section for the production of direct electron pairs by heavy ions in emulsion have been performed. Nuclear track emulsions were exposed to the 1.8 GeV/amu Fe^{56} beam at the Lawrence Berkeley Laboratory bevalac and to the 60 and 200 GeV/amu O^{16} and the 200 GeV/amu S^{32} beam at the European Center for Nuclear Research Super Protron Synchrotron modified to accelerate heavy ions. The calculations combine the Weizsacker-Williams virtual quanta method applicable to the low-energy transfers and the Kelner-Kotov relativistic treatment for the high-energy transfers. Comparison of the measured total electron pair yield, the energy transfer distribution, and the emission angle distribution with theoretical predictions revealed a discrepancy in the frequency of occurrence of the low-energy pairs ($\leq$10 MeV). The microscope scanning criteria used to identify the direct electron pairs is described and efforts to improve the calculation of the cross section for pair production are also discussed.

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TECHNICAL MEMORANDUM

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I. INTRODUCTION

The principal goal of this study has been to develop a practical method which employs only the electromagnetic interaction to measure the energy of ultrarelativistic heavy ions in the energy region above 10^{13} eV/amu (10 TeV/amu). The only apparent electromagnetic phenomenon that may be used is the materialization of electron-positron pairs from the virtual photon field of the relativistic ion in the field of a stationary nucleus. This is a phenomenon which has been studied experimentally for more than 35 years without resolving differences between measurements and calculations, and thus is still an interesting aspect of quantum electrodynamics (QED). Until the last several years, work on this phenomenon has been limited to primary particles from cosmic ray air showers (electrons and mu-mesons), a few heavy primary cosmic ray nuclei, and protons and π-mesons from accelerators. The yield of direct Coulomb pairs from the singly charged primary particles has been less than one per meter in the typical production and detection medium (nuclear track emulsions), and thus a definitive experimental study has been hampered. The recent availability of heavy ions with high energy at the European Center for Nuclear Research (CERN) has opened the opportunity to resolve the previous experimental uncertainty and confirm the yield of direct Coulomb pairs.

Present techniques for measuring particle energy which employ electromagnetic phenomena such as Cerenkov counters and the relativistic rise of ionization in gas-filled counters (ion chambers and scintillators) saturate below 1 TeV/amu for practical detectors. Transition radiation detectors have been designed to measure cosmic ray energies to about 10 TeV/amu. Only "ionization calorimeters" that depend on the strong (nuclear) interaction have been accepted as practical energy measuring devices above 10 TeV/amu. Calorimeters require enough depth that the primary particle interacts (nuclear) in the device and produces a cascade of hadronic (p, π, K, etc.) and "electromagnetic" particles (e, γ), the number of which are sampled to estimate the primary energy. At 10^{14} eV/amu this requires at least 5 cm of lead for thin lead-x-ray film-emulsion calorimeters, $\gtrsim$30 cm of lead for "total absorption" calorimeters of lead-scintillator, or $\gtrsim$15 m water equivalent depth in the atmosphere for air shower arrays. In addition to the mass of material required for ionization calorimeters, there are serious concerns about possible changes in the behavior of nuclear interactions beyond 10^{14} eV, particularly for heavy nuclei. Part of these concerns has been generated by conflicting results of air shower experiments which, by various analysis techniques, have indicated that cosmic rays are either mostly protons or mostly iron near 10^{15} eV. Other concerns about nuclear interactions at high energy stem from the theory of strong interactions, quantum-chromodynamics (QCD). QCD predicts for heavy nucleus interactions a phase change of nuclear matter from bound quarks in neutrons and protons to a plasma of the constituent quarks and gluons. This would probably result in a quite different particle cascade in calorimeters.

appropriate primary ions since the production of bremsstrahlung will be reduced according to the ratio $[m_e/M]^2$. Energetic muons, pions, and protons were studied [6-11] after particle accelerators, which produced high energy monoenergetic beams, became available in the late 1960's and early 1970's. A beam of 200 GeV protons at the Fermi National Accelerator Laboratory was utilized to produce direct electron pairs in an emulsion [10-11]. The results are included in Figure 1. A small sample of heavy cosmic ray tracks, taken from emulsions exposed on "Intercosmos-6" [12], was examined for direct pairs and the yield is included in Figure 1. This cosmic ray data of Grigorov et al. [12], although limited by poor statistics, inexplicably reported a higher value than the proton accelerator measurements even though the reported pair energies are very high. Fortney et al. [9] used a Ne-H_2 bubble chamber in a 25-kilogauss magnetic field to measure the momentum and yield of pairs above 10 MeV/c. The results matched their calculations of the yield and pair momentum spectrum. If adjusted for the high pair momentum cutoff, and for the target and the projectile atomic numbers, this result would fall close to (▲) in Figure 1. However the appropriate pair momentum cutoff adjustment is presently uncertain as discussed in section VI.

Heavy ion beams have become available in recent years first at 2 GeV/amu (Berkeley), then at ~10 GeV/amu (Brookhaven), and more recently at 60 and 200 GeV/amu (CERN-Geneva). We exposed nuclear track emulsions to all these beams and have scanned significant track lengths of most exposures to determine the linear frequency of pairs. Results of various individual measurements in this study are included in Figure 1. Present direct electron pair yields have increased commensurate with the ability to recognize the lower energy pairs. The initial problem in detecting these low-energy electron pairs ($e \lesssim 10$ MeV) was due to the fact that the division of the energy between the electron and the positron can be so disparate that it was difficult to recognize the lower energy electron (positron) as a member of a pair and to trace the lower energy electron (positron) to a common interaction vertex. Although the lower energy pairs are generally accompanied by larger angles between the primary particle and the members of the pair they are not strictly correlated to pair energy, a consequence of the five-body nature of the physical phenomenon. These aspects, covered in detail below, make the lowest energy pairs difficult to recognize. This is especially true of electrons ($e_- \leq 1$ MeV) that can either be mistaken for delta rays or are missed altogether due to the background. The data from proton tracks cited above are consistent with this assessment since they detected only the highest energy pairs resulting in a low yield. The recognition of these problems resulted from new calculations of pair energy and angle distribution and also a new scanning technique and electron energy measurements described below.

III. SUMMARY OF CALCULATIONS

To better understand the physical properties of the direct electron pairs, calculations have been performed that predict the total yield, the energy transfer during the collision, the energy sharing, the net transverse momentum, and the angular distribution of the pairs. The standard theory is defined to be the lowest order quantum electrodynamic (QED) evaluation of the total cross section for pair production by heavy ions in emulsion. Calculations [13-20] dating back to the 1930's include both the classical and QED

treatments of this problem where some approaches have taken into account the atomic screening of the absorber. Computational efforts reported here have focused on the Weizsacker-Williams (WW) method of virtual quanta as described in [21], including corrections for pair production by low-energy photons (Racah formula [22]) and higher order corrections [23,24] for relativistic pairs (i.e., $e_+ >> 1$ and $e_- >> 1$). Also included are higher order terms involving the effective atomic number of the target. The region of validity for the WW method is determined by two conditions: (1) the Lorentz factor for the heavy ion (γ) is much greater than one, and (2) the energy transfer ($\epsilon/m_e c^2$) is much less than (γ). One of the shortcomings of the WW method is that it depends on an undetermined parameter which corresponds, in this case, to the minimum impact parameter. Fortunately another method that evaluates the direct pair production cross section (Kelner and Kotov (KK) [18]) has no undetermined parameters but is valid only in the relativistic energy transfer region. If one matches the results of the KK and the WW calculations in an energy transfer region where both should be valid, then the minimum impact parameter is determined (see P. Eby [25] for more details). The total estimated yield for $\gamma = 200$ is shown in Figure 1 (+ symbol) and should be compared with the most recent measured yield (sulfur - solid triangle) that reflects the current scanning criteria. The corresponding total energy transfer curve ($dN/d\epsilon$) is compared to the same set of electron pair data taken from the CERN sulfur exposure (Figure 2). It is quite evident that there is a measured overabundance of the low-energy pairs compared to the theoretical estimate. This discrepancy is being examined from two sides. Do the computations accurately predict the frequency of the low-energy pairs and is there any systematic bias in identifying the low-energy pairs in the emulsion? These questions are discussed in section VI.

IV. DESCRIPTION OF ACCELERATOR EXPOSURES

The EMU04 emulsion experiment design [26] is illustrated in Figure 3. The basic configuration is a stack of 20 thick emulsion plates (800 μ acrylic substrate with 500 μ of Fuji 7B emulsion coated on both sides) oriented parallel to the beam and housed in a light-tight black plastic box with a thin window facing the beam. The emulsion pouring was accomplished at the Fermi National Accelerator Laboratory in Batavia, Illinois. The total exposure of the emulsion plates to the heavy ion beam at the CERN SPS was controlled by a programmable deflector magnet. The magnet was positioned approximately 2,000 m upstream of the target area where a preselected fraction of the heavy ions are deflected from the main beam. The normal beam intensity had to be reduced so that the ion events could be analyzed in the emulsion without interference from neighboring events. This was achieved by defocusing the beam so that a beam intensity of 2,000 to 3,000 ions cm^{-2} was obtained. Thus the central intensity, lateral spread, and ion purity were carefully monitored. Figure 4 shows the beam access area where each of the EMU04 emulsion stacks were exposed to two separate beam spills displaced 1 cm apart. The TV monitor displayed the beam profile which assisted the operator in timing the insertion of the emulsion targets. Just after the exposure and before the plates were developed, a reference grid was photographed on one side of each emulsion plate. This grid contained a pattern of numbers that allowed unique identification of primary tracks.

Over the past several years the EMU04 emulsion plates have been exposed to the 60 and 200 GeV/amu oxygen beams and the 200 GeV/amu sulfur beam at the CERN SPS. Preceding the CERN heavy ion exposures, emulsion stacks of a similar design were exposed to a 1.8 GeV/amu Fe beam at the Lawrence Berkeley Laboratory (LBL). Figure 5 is a microphotograph mosaic of a typical direct electron pair in the emulsion oriented close to the focal plane of the microscope. The heavy primary ion is S^{32}.

V. MICROSCOPE SCANNING: TECHNIQUES AND RESULTS

A total of 50 m of heavy ion tracks have been scanned with a magnification of 1000. Figure 6 shows the measured pair yield as a function of distance from the edge of the emulsion plate. The yield is being gradually attenuated as the track length increases. This is caused by (1) a nuclear interaction prematurely terminating the direct pair search, (2) the background level building up with track length in the emulsion making it more difficult to observe the pairs, and (3) the tracks not being perfectly parallel with the substrate (i.e., the dip angle is not zero), therefore, the lateral spread results in a distribution of track lengths. Hence the first scanning rule is that the pathlength/track is limited to 3 cm from the edge of the emulsion plate. The initial set of measurements of pair frequency in this study is shown in Table 1. These results, normalized to 3 cm of track length and to Fe ions (by Z^2), are plotted in Figure 1 ($\Delta,\theta,\theta,\emptyset$). They are above previous measurements with proton beams, but below previous and our recent calculations. Examination of calculations of production angles and energy sharing between electrons indicated that low-energy electron pairs were being missed. An exercise with different scan rates (shown in Table 1) indicated a scan rate of ~1 cm/hr should be the upper limit with experienced scanners. Because of the low yields of these measurements a new scanning procedure was developed by D. T. King [27]. Additionally, the measurement of the energy of each electron was adopted, as well as their angles with respect to the primary. The scan procedure and electron energy measurement procedure are described below. The result of scanning with this procedure is given in Figure 1 (▲).

The latest procedure is as follows. Scan at 1000 magnification at a rate of $\lesssim$1 cm/hr, focussing at each field of view over the depth >20 μ above and below the primary particles track. Note every knock-on electron of energy >2 MeV (the range is at least one field of view and in the same general direction although it may be scattered). The energy of the electron is measured by recording three deflection readings for the multiple-scattering angle over a track length of 200 μ. The average multiple-scattering angle is inversely proportional to the electron's momentum. For the case of sulfur, an average of 10 knock-on electrons/cm was found. This is compatible with the theoretical probability per unit pathlength of the production of a knock-on electron with energy e_-:

$$\omega(E,e_-) = \frac{2\pi N Z^2 q^4}{m_e c^2 \beta^2 (e_-)^2}\left[1 - \frac{\beta^2(e_-)}{(e_-)_{max}}\right], \qquad (1)$$

where N is the number of electrons per unit volume, $E(\beta)$ is the incident energy of the primary ion, Z is the atomic number of the primary particle, and q is the electron charge. Also the emission angle is given by

$$\cos\theta \approx \frac{1}{\beta}\sqrt{\frac{(e_-)}{(e_-) + 2m_e c^2}} \tag{2}$$

and

$$(e_-)_{max} \approx 2m_e c^2 \beta^2 \gamma^2 \tag{3}$$

for $m_e/M \ll 1$; M is the mass of the heavy ion. Since $\gamma = 200$, then $(e_-)_{max} \approx 4.1 \times 10^4$ MeV, $\beta \approx 1$ and so

$$\omega(E,e_-) \approx \frac{2\pi N Z^2 q^4}{m_e c^2}\left[\frac{1}{(e_-)^2}\right] . \tag{4}$$

Having found a knock-on electron, examine each origin grain for an associated track with $e_- \geq 1$ MeV. This energy is a practical lower limit because the energy uncertainty approaches 50 percent. For a bonafide electron pair the origin grain of the electron (positron) must be within 1 μ of the primary track and the origin grain of each associated track must be within 2 μ of each other. With this criterion, it is estimated that 1-2 percent of the candidate pairs will be false. This background depends on the chance coincidence of a delta ray of energy $e_- < 1$ MeV and a fast knock-on electron of several MeV.

A correlation plot (Figure 7) of the emission angle vs. the energy has been generated [27] for a subset (101 pairs) of the 200 GeV/amu sulfur electron pair data found with the latest scan method described above. Not unexpectedly, the maximum emission angle is inversely proportional to the energy but there is a large distribution of angles at each energy. The total energy transfer in the interaction (Figure 2), the energy division between the electron and positron (Figure 8), the net transverse momentum of the pairs (Figure 9), and the angular distribution for the electrons/positrons (Figure 10) have all been derived from this same 200 GeV/amu sulfur electron pair data set.

VI. DISCUSSION AND FUTURE WORK

To resolve the question of whether the latest observed high yield of the low-energy pairs is contaminated by some background effect in the emulsion, improved calculations of the cross section for pair production by relativistic heavy nuclei [25] will be incorporated into a Monte Carlo simulation of the pair production process and compared to the data. The Monte Carlo simulation will be based on the Weizsacker-Williams virtual quanta method. The theoretical curves in Figures 2 and 10 are a result of the WW method. Further

measurements on oxygen ion tracks at 200 GeV/amu and 60 GeV/amu will be performed for this comparison.

The differential cross sections that will be randomly sampled in the Monte Carlo simulation are

$$\frac{d\sigma_{ww}}{de} = N(e)*\sigma_B(e), \tag{5}$$

where N(e) is the Weizsacker-Williams frequency distribution for the virtual quanta, the energy transfer e = virtual photon energy, and $\sigma_B(e)$ is the Racah expression [23] for the pair production by photons.

$$\frac{d\sigma_{NS}}{de_+} = \begin{array}{l}\text{Bethe-Heitler formula} \\ \text{3D-1000 in [22].}\end{array} \tag{6}$$

This cross section, differential in positron energy, is based on the first Born approximation with a non-screened nucleus.

$$\frac{d\sigma_{NS}}{d\theta_+} = \int_e \int_{e_+} \frac{d^2\sigma}{de_+ d\Omega_+} N(e) de_+ de \ . \tag{7}$$

This cross section, differential in positron energy and solid angle, is the Sauter-Gluckstern-Hall formula (3D-2000 in ref. [22]) and is weighted with the Weizsacker-Williams distribution. Once again it applies for an unscreened point nucleus.

A theory that has no free parameters and yet is applicable to the low-energy transfer pairs will be pursued.

In the near future, an examination of some of the Japanese-American Collaborative Emulsion Experiment (JACEE) cosmic ray data will be done in order to compare the direct electron pair yield with the corresponding values calculated from the calorimeter energy estimates. Additional CERN experiments with a Pb beam, to be available in 1991, are planned since the increased electron pair yield may resolve any remaining observational problems as well as validate the calculations.

This study has not yet elevated the measurement of the direct Coulomb pair yield to an energy measuring technique. It has, however, made considerable progress in both theory and observations that may allow in the near future the resolution of long standing discrepancies between various experimental results, and between calculations and observations of this interesting aspect of quantum electrodynamics.

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27. Measurements on this subset of 200 GeV/amu sulfur data were performed by Professor David T. King of the University of Tennessee.

TABLE 1. SUMMARY OF THE MEASURED DIRECT ELECTRON PAIR YIELD. (THE Fe^{56} DATA WERE TAKEN FROM THE LBL EXPOSURE WHILE THE O^{16} AND S^{32} DATA WERE ACQUIRED AT CERN.)

Projectile	Primary Energy (GeV/nuc)	Track (cm)	Pairs	Jets	Yield (pairs/cm)
Fe^{56}	1.8	96.4	27	--	0.280±0.050
O^{16}	60.0	978.0	46	90	0.047±0.007
O^{16}	200.0	2959.0	270	218	0.091±0.006
S^{32}	200.0	979.6	215	120	0.219±0.015(a)
S^{32}	200.0	129.4	40	16	0.309±0.049(b)

(a) = 20 cm/day
(b) = 5 cm/day

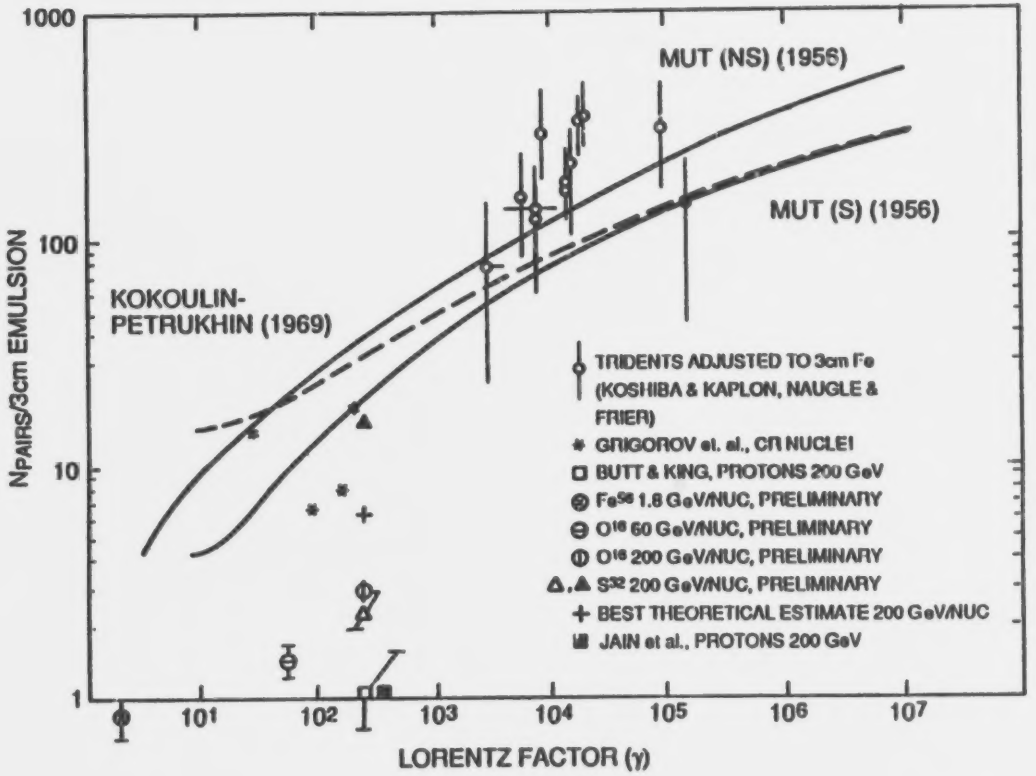

Figure 1. The yield of direct electron pairs produced in nuclear track emulsion by various primary projectiles (electrons, protons, oxygen, sulfur, iron) and several cosmic ray nuclei. The yields have been normalized to the equivalent yield of an Fe nucleus in 3 cm of emulsion. The solid curves are the theoretical predictions of Murota-Ueda-Tanaka [17] for both the screening and non-screening case and the dashed curve is due to Kokoulin-Petrukhin [20]. The "best theoretical estimate" (+ symbol) at 200 GeV/amu is a combination of the Weizsacker-Williams method [21,22] matched to the Kelner-Kotov prediction [18,19] in the intermediate energy transfer region, e ≈ 10 MeV [26].

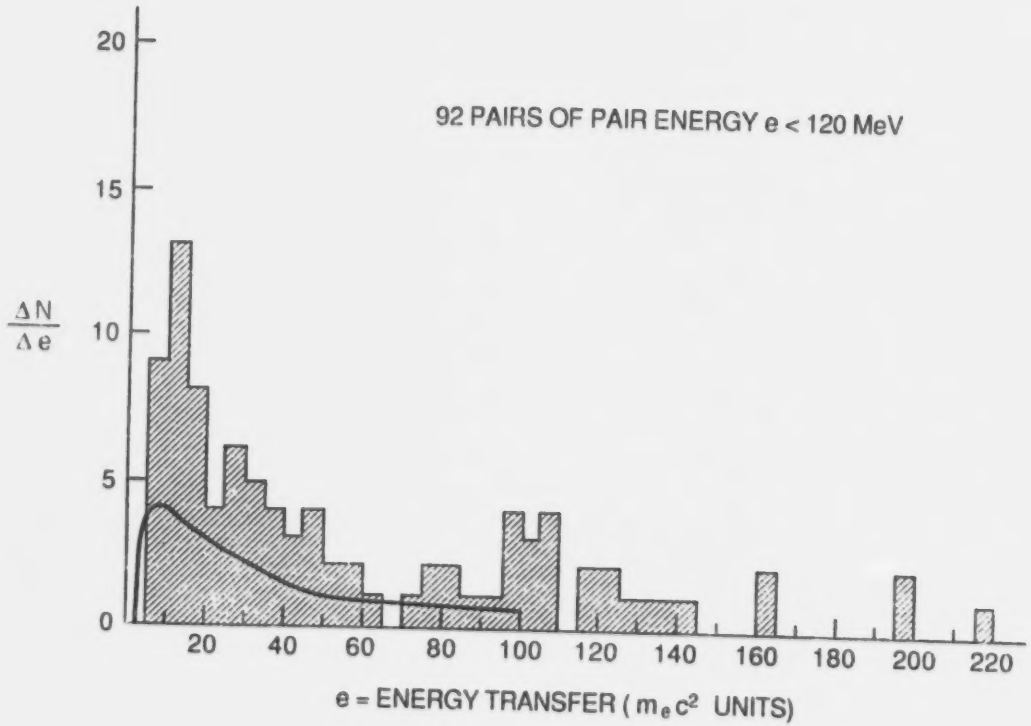

Figure 2. The energy transfer distribution for the direct pairs derived from a subset of the 200 GeV/amu Sulfur data [27]. The solid curve is a result of the Weizsacker-Williams-Kelner-Kotov calculation described in [26].

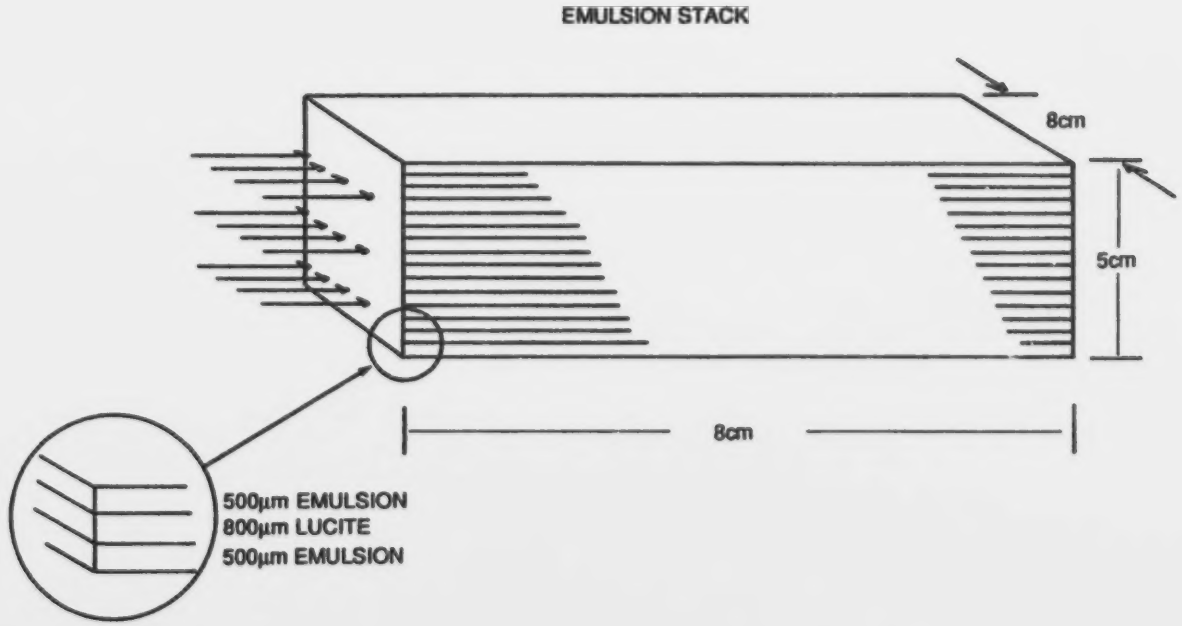

Figure 3. An illustration of the EMU04 emulsion stack that was exposed to the accelerator heavy ion beams at CERN and LBL.

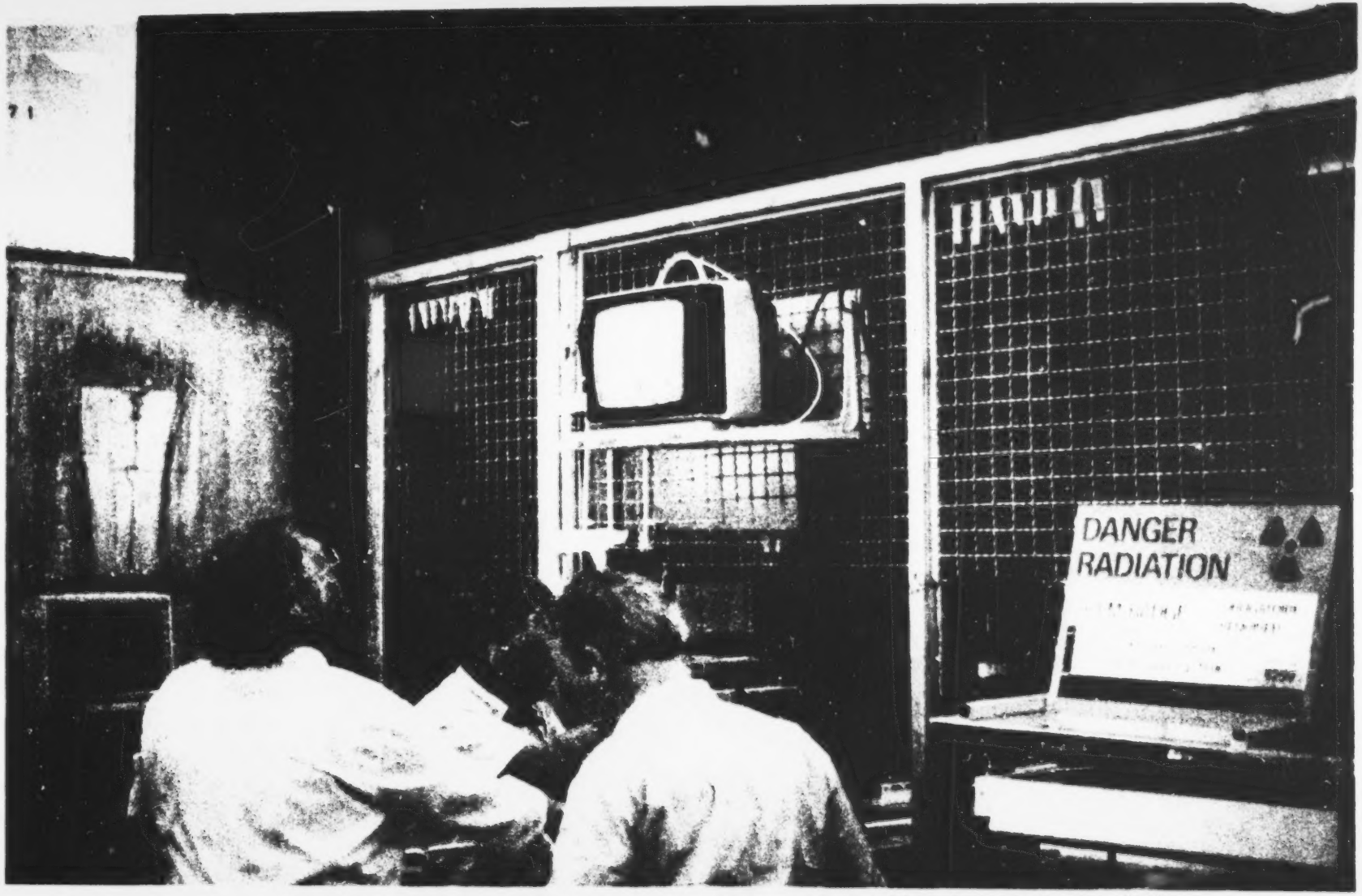

Figure 4. Target insertion into the ion beam accomplished with the knowledge of the beam profile displayed on the overhead TV monitor.

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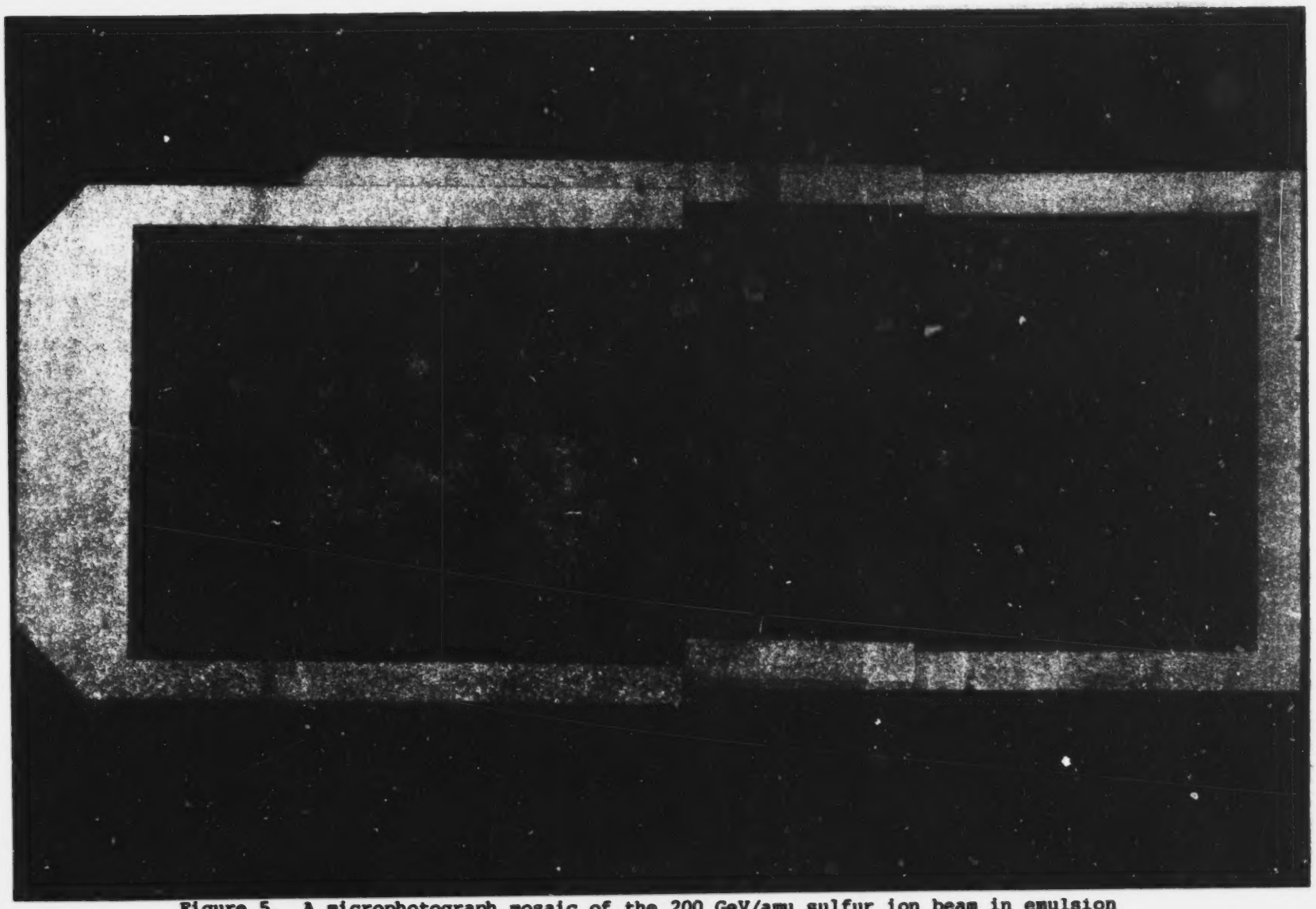
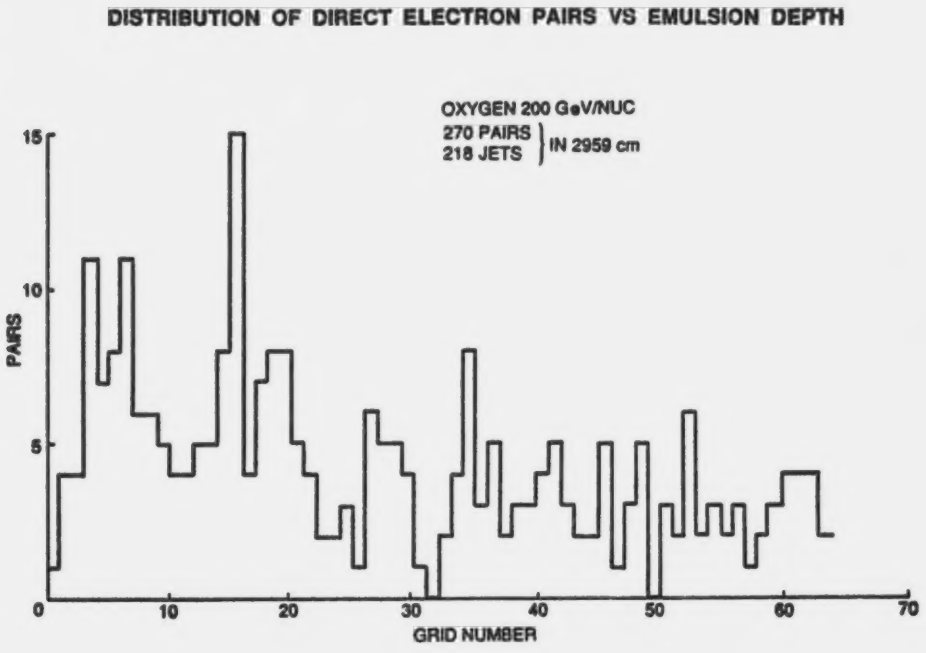


Figure 5. A microphotograph mosaic of the 200 GeV/amu sulfur ion beam in emulsion including a direct electron pair originating on the left side of the photograph and traveling to the right.



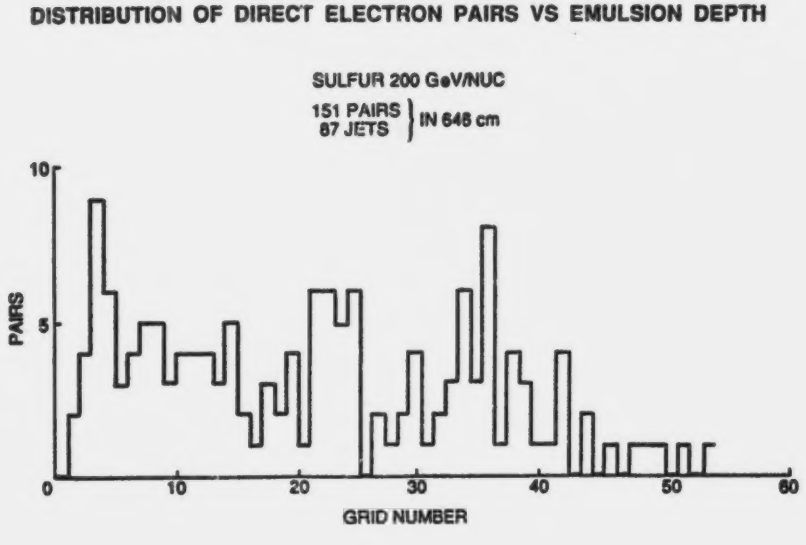


Figure 6. Distribution of the direct electron pairs as a function of the distance from the edge of the emulsion plate for both the 200 GeV/amu oxygen and sulfur CERN exposures.

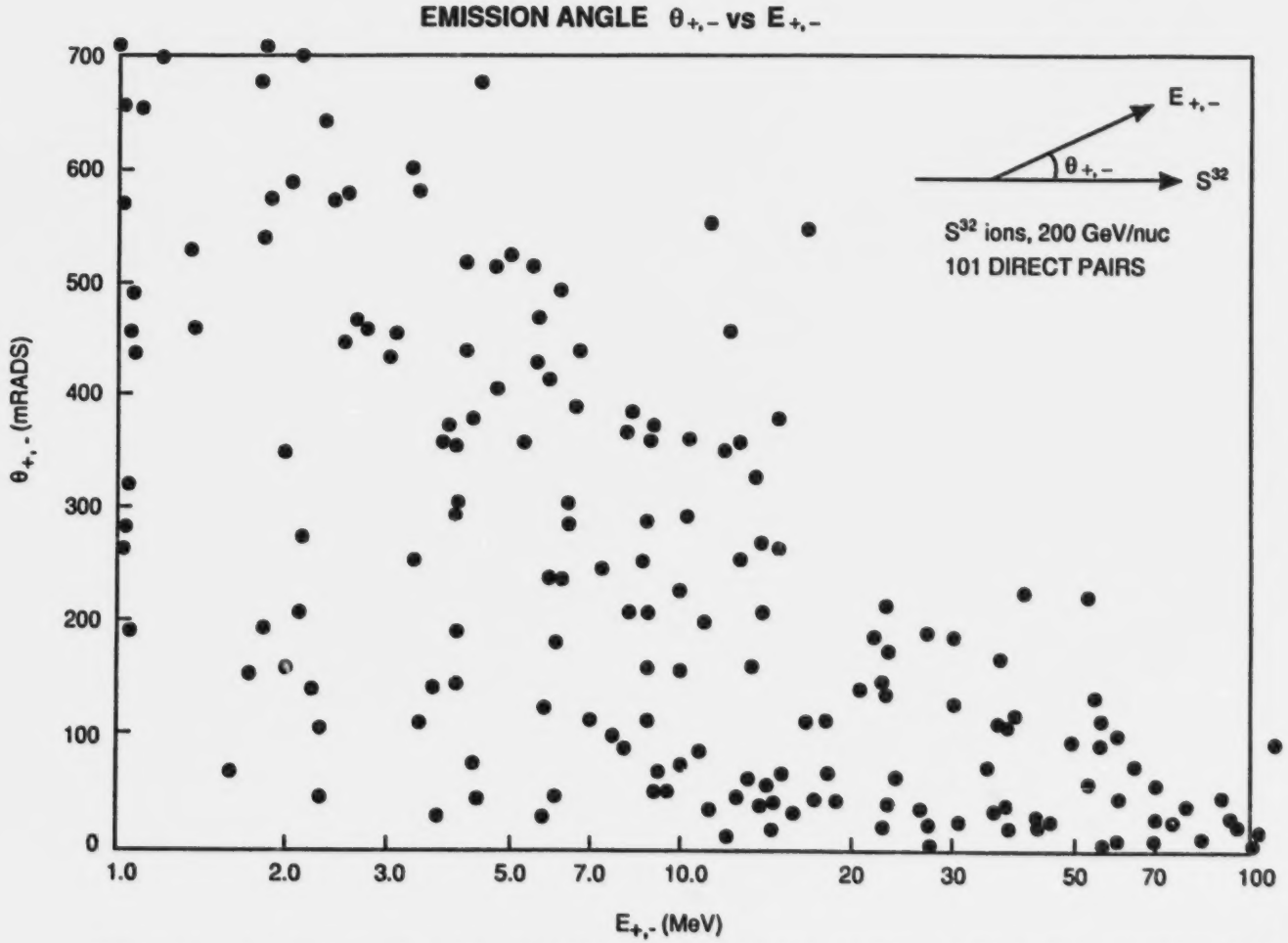


Figure 7. A scatter plot of the individual emission angles of both the electron and positron of the direct pair versus their respective energies for a subset (101 pairs) of the 200 GeV/amu sulfur data [27].

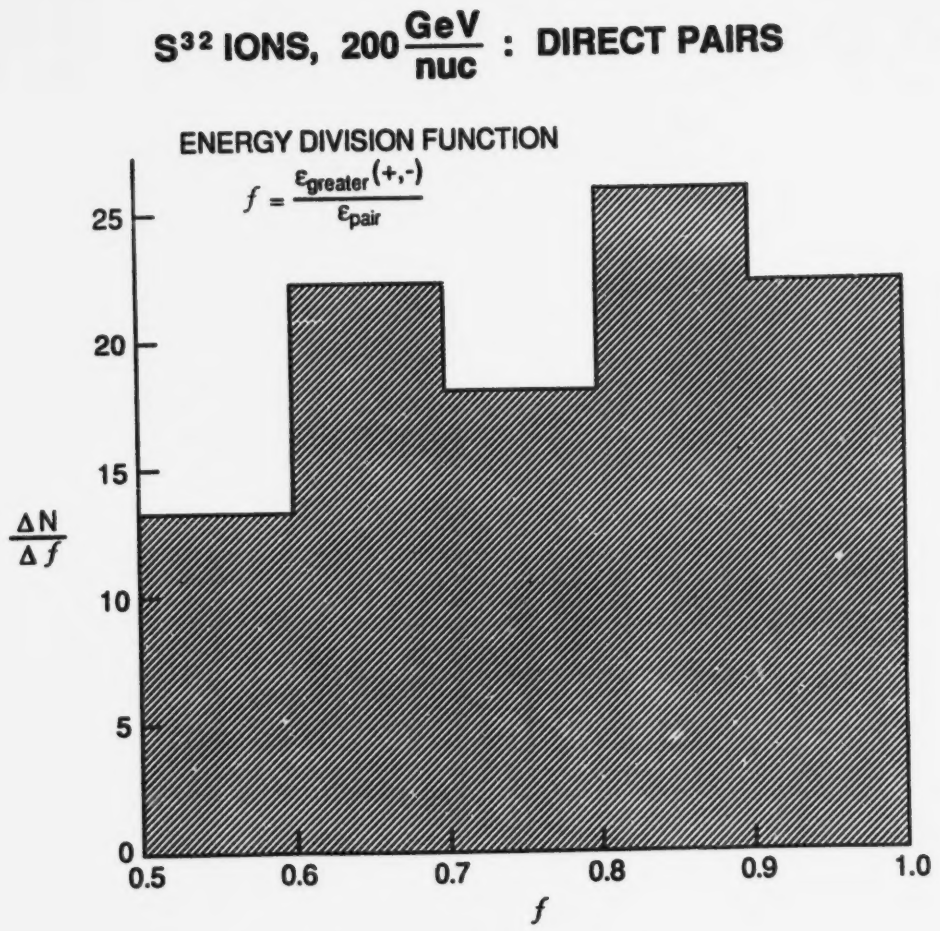


Figure 8. A histogram of the energy division between the electron and positron of the direct electron pairs derived from the sulfur data set of Figure 7.

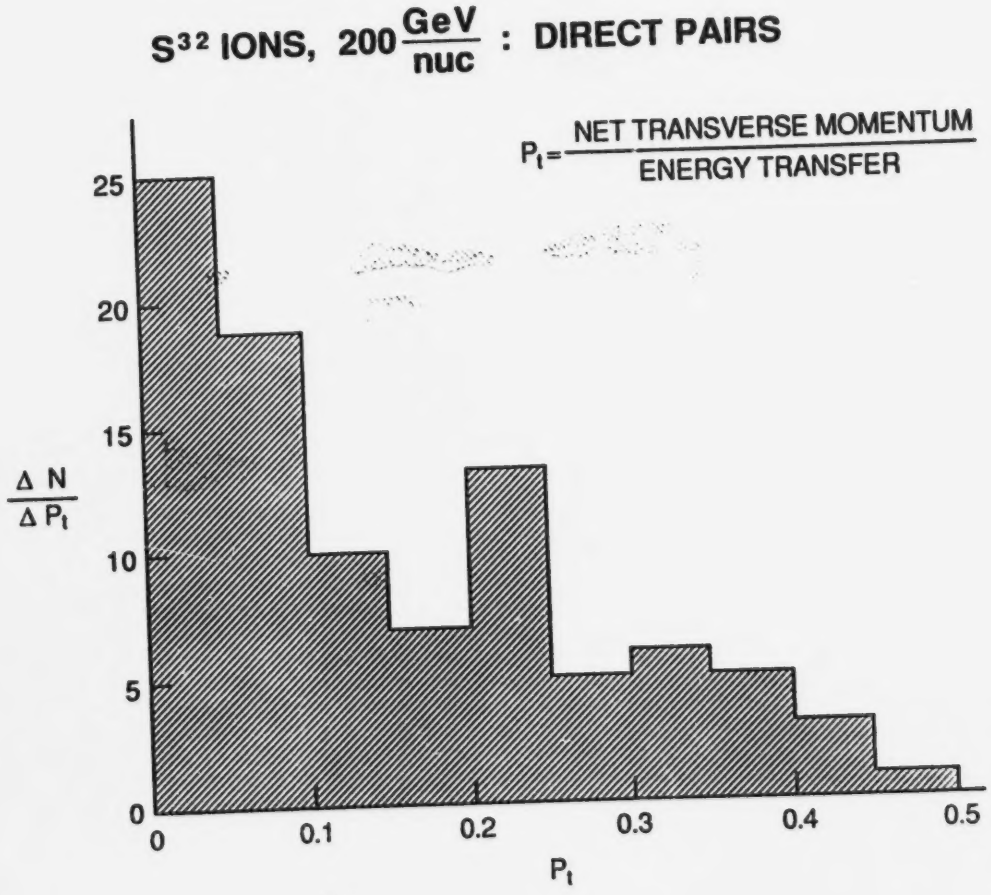


Figure 9. The frequency distribution of the net transverse momentum for the direct electron pairs deduced from the subset of sulfur data referenced in Figure 7.

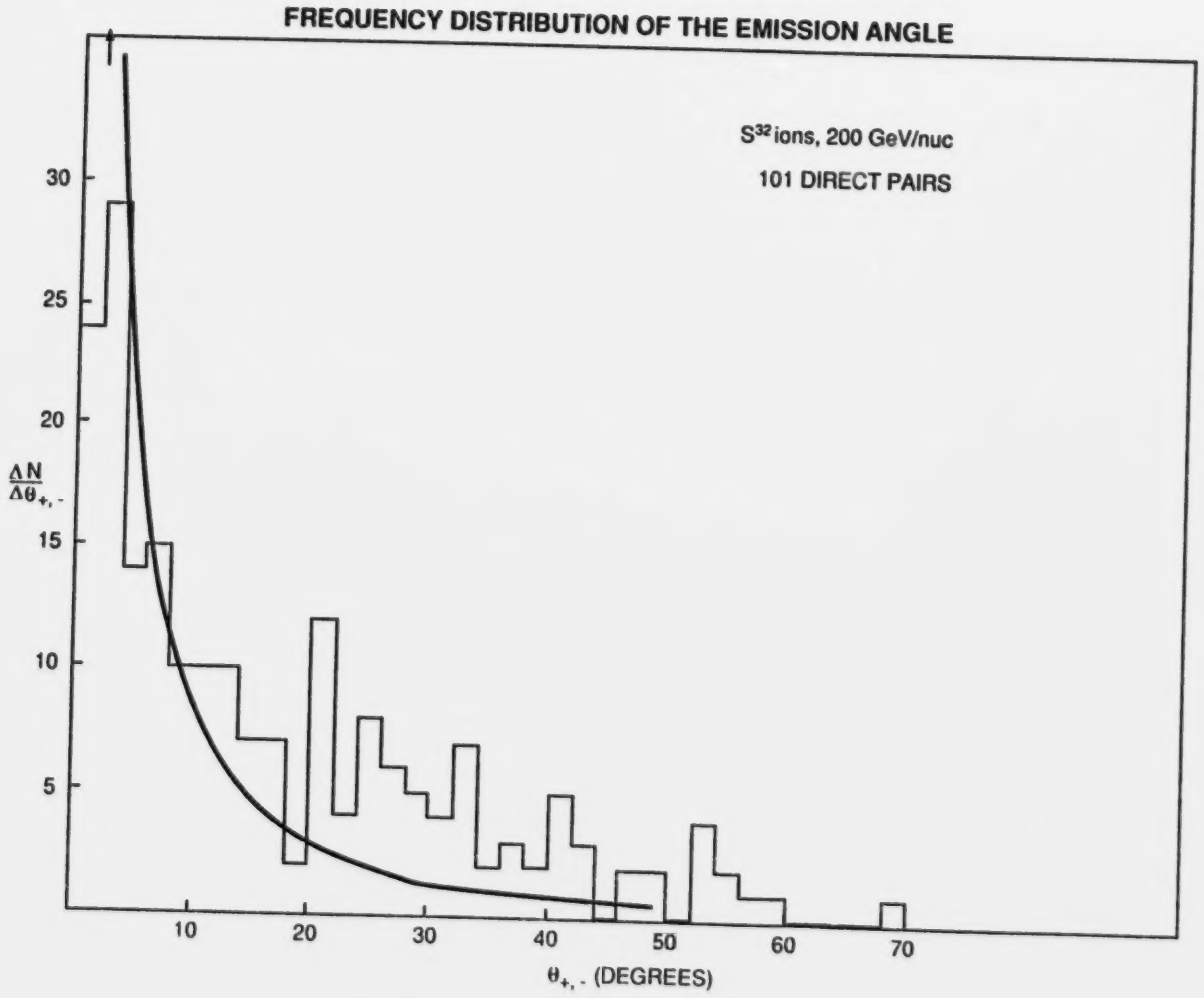


Figure 10. The frequency distribution of the emission angle for both the electron and positron of the direct electron pairs taken from Figure 7. The curve is a prediction based on the formula (7) of Section VI.

APPROVAL

MEASUREMENTS AND CALCULATIONS OF THE COULOMB CROSS SECTION FOR THE PREDICTION OF DIRECT ELECTRON PAIRS BY ENERGETIC HEAVY NUCLEI IN NUCLEAR TRACK EMULSION
Center Director's Discretionary Fund Final Report

By J. H. Derrickson, P. B. Eby, W. F. Fountain, T. A. Parnell,
B. L. Dong, J. C. Gregory, Y. Takahashi, and D. T. King

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

E. Tandberg-Hanssen

E. TANDBERG-HANSSEN
Director
Space Science Laboratory